

Article

How Evaluation Frameworks Shape the Economic Value of Vessel Traffic Service: Evidence from Full-Sample Vessel Trajectories

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Highlights

- This study develops a full-sample trajectory-based evaluation framework for complex maritime coordination systems, demonstrating how operational data can improve the assessment of digital governance performance.
- The framework integrates heterogeneous operational records and trajectory-level evidence to reveal how evaluation mechanisms shape the visibility of system-level value.

Main findings and implications

- The full-sample framework identifies substantially higher VTS economic value than traditional sampling-based approaches and reveals routine coordination as a major source of operational benefits.
- The findings suggest that evaluation of data-driven infrastructure systems should move beyond exceptional-event assessment toward continuous monitoring of distributed operational effects.

Abstract

Economic evaluation of Vessel Traffic Service (VTS) has long relied on sampling-based observations and average-cost assumptions, yet limited attention has been paid to whether evaluation frameworks themselves shape how the value of digital maritime governance is identified and represented. Drawing on full-sample vessel trajectories and dispatch records from a major Chinese hub port during 2018–2020, this study develops a parallel comparative design to compare a traditional sampling-based framework with a full-sample evaluation approach under identical traffic conditions. The results show that differences in evaluation frameworks affect not only the overall magnitude of estimated benefits, but also their composition. Compared with the traditional approach, the full-sample framework generates substantially higher estimates of economic value and assigns greater importance to routine coordination, where repeated small operational adjustments accumulate over time. By contrast, weather disruptions and channel-constrained coordination become relatively less prominent. These differences appear to be associated with variation in temporal benchmarks, sample coverage, and cost assignment strategies. Rather than identifying a single “correct” valuation, the study highlights the sensitivity of VTS economic assessment to methodological assumptions and suggests that, in digitally coordinated public infrastructure systems, evaluation frameworks may shape which forms of governance value become visible and incorporated into policy and investment decisions.



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Keywords: vessel traffic service (VTS); economic evaluation; full-sample trajectory data; digital maritime governance; evaluation frameworks; port traffic management

1. Introduction

Maritime governance plays a critical role in ensuring the safety and efficiency of global seaborne trade. As a core instrument of port traffic management, Vessel Traffic Service (VTS) has long been responsible for vessel monitoring, traffic organization, and navigational risk warning. With the development of Automatic Identification Systems (AISs), sensor technologies, and data analytics, VTS has gradually evolved from a conventional safety-support tool into a digital governance system that also supports traffic coordination, efficiency improvement, and operational risk management [1]. This functional expansion raises a practical question: how should the economic value generated by VTS be assessed?

Cost–benefit analysis (CBA) has long been widely used in the appraisal of transport infrastructure and public investment projects [2–4]. Navigation and Lighthouse Authorities (IALA) introduced a CBA framework to support the planning and evaluation of VTS systems [5]. Unlike revenue-generating transport infrastructure, VTS is typically provided by governments as a public service, and much of its operational value is not directly reflected through market transactions [6]. Similar challenges have been widely discussed in the valuation of non-market public services, where the benefits of public parks, healthcare, education, or environmental amenities often need to be approximated through indirect or proxy-based valuation approaches rather than direct prices [7–9]. In the case of VTS, operational benefits commonly take the form of reduced waiting times, improved traffic efficiency, congestion mitigation, and risk reduction, making them difficult to capture through conventional financial indicators [10]. As a result, estimating the “benefit” component of VTS evaluation has remained a persistent methodological challenge. To address this issue, a range of quantitative approaches has emerged to approximate the operational and economic benefits generated by VTS.

Earlier studies and administrative practices commonly relied on expert judgment, survey-based estimation, or limited-sample extrapolation to approximate operational benefits, while later studies increasingly adopted performance-oriented approaches such as DEA and multidimensional evaluation models [11,12]. Although these approaches are effective for benchmarking performance and efficiency ranking [13,14], their outputs often take the form of relative scores or dimensionless rankings, making them less suitable for addressing policy demands related to budget allocation, investment appraisal, and monetized benefit estimation. Therefore, sampling-based CBA continue to play an important role in practical VTS evaluation despite increasing data availability.

Yet comparatively limited attention has been paid to the implications of evaluation frameworks for how VTS value is identified and represented. Existing studies generally treat evaluation approaches as neutral measurement tools, with limited discussion of how methodological choices may influence what forms of value become observable. For VTS systems that depend heavily on continuous coordination and real-time traffic organization, decisions regarding sample coverage, temporal scale, and cost assignment may affect not only the magnitude of estimated benefits but also how different coordination activities are represented in economic evaluation. Different evaluation frameworks may therefore do more than produce different numerical estimates [15]. They may also influence how the governance value of VTS is interpreted [16].

Against this background, this study addresses a central question: to what extent do different evaluation frameworks shape the identification and representation of VTS

economic value? Drawing on full-sample vessel trajectories and dispatch records from a major Chinese hub port during 2018–2020, the study develops a parallel comparative design to compare a traditional sampling-based evaluation framework with a full-sample framework under identical traffic conditions. By holding the operating environment constant, the study seeks to identify how valuation outcomes vary across evaluation frameworks and to explore the factors potentially associated with these differences.

This study contributes in two ways. Empirically, it provides comparative evidence based on trajectory-level full-sample data, showing that traditional sampling approaches may understate the cumulative contribution of routine coordination while altering the relative value structure across coordination scenarios. Methodologically, this study develops a full-sample trajectory-based evaluation framework that enables direct comparison between alternative valuation approaches under identical operational conditions. Rather than treating evaluation methods as neutral measurement tools, the proposed framework provides a way to examine how methodological choices influence the identification and representation of governance value. The broader implication is that high-resolution operational data can be used not only to improve measurement precision, but also to better understand how governance value becomes visible through evaluation itself.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 introduces the research design, data sources, and evaluation methods. Section 4 presents the empirical results. Section 5 concludes with a discussion of the findings and their policy implications.

2. Literature Review

2.1. The Evolution and Constraints of VTS Evaluation Approaches

Evaluation practices for VTS have gradually evolved alongside improvements in operational data availability. Early studies largely approached VTS as an infrastructure investment project. Guidelines issued by the IALA established CBA as the standard framework for assessing investment feasibility [17]. Under limited data conditions, early evaluations relied heavily on expert judgment or small-scale samples [18], often treating VTS as a relatively static physical asset rather than an active traffic management system characterized by continuous coordination [19].

As VTS systems became more widely implemented during the 2010s, research attention gradually shifted from feasibility assessment to more detailed analysis of operational benefits [19]. Scholars introduced approaches such as fuzzy comprehensive evaluation [20], questionnaire-based assessment [21,22], and DEA to construct multidimensional performance evaluation systems. Some studies have also begun to examine broader economic spillover effects by applying input–output models to estimate the wider socioeconomic contributions of VTS systems [23].

Despite these methodological developments, many evaluation approaches continued to rely on partial observations and simplifying assumptions. Most studies remained dependent on limited statistical samples or survey-based information and commonly assigned operating costs based on vessel-type averages. As a result, valuation outputs often reflected static snapshots of specific periods rather than continuous measurements of traffic flow. Although the release of IALA Guideline G1131 in 2021 signaled growing international interest in updating evaluation methods, the guideline largely retained the conventional CBA structure and offered limited operational guidance for using full-sample operational data.

This situation points to an enduring methodological challenge. Traditional CBA frameworks necessarily simplify continuous maritime traffic flows into discrete and observable events, yet the simplification process itself may shape valuation outcomes. Choices regard-

ing which vessels are included, what periods are observed, and how cost heterogeneity is handled can all influence how operational value is represented. More broadly, conventional evaluation tools may struggle to capture dispersed or indirect forms of governance value, particularly when benefits emerge through coordination and system-level efficiency rather than direct market transactions [24]. These considerations provide a useful starting point for examining how evaluation frameworks may influence the visibility of VTS governance value [25].

2.2. *The Shift Toward Full-Sample Trajectory Data in Transport Economics*

The methodological limitations observed in maritime evaluation stand in notable contrast to broader developments in transportation economics.

In maritime transport, the increasing availability of AIS trajectory data has enabled more detailed assessments of vessel movements and operational efficiency [26]. For example, Feng et al. [27] developed a trajectory-based framework to evaluate vessel time efficiency within port areas using AIS-derived space and time paths. In land transport research, the growing availability of high-resolution trajectory data has encouraged a gradual shift from sample-based extrapolation toward full-sample analysis. Souleymane & Harris [28] demonstrated how trajectory data can replace static estimation approaches to improve the measurement of infrastructure benefits. Using large-scale vehicle trajectory datasets, Li et al. [29] showed that conventional models may smooth out substantial variation in congestion costs and inadequately represent the spatial and temporal dynamics of traffic congestion. Koch et al. [30] further argued that evaluating complex transport systems increasingly requires full-sample tracking rather than static averages, since averaging procedures may obscure important heterogeneity embedded in dynamic system behavior.

These developments offer direct implications for maritime evaluation. Maritime traffic shares several key characteristics with land transport systems, including heterogeneous vehicles, dynamic environmental constraints, and a hybrid operational structure combining centralized coordination with decentralized decision-making. Yet maritime evaluation methods have not experienced a comparable shift toward higher observational granularity. Zheng et al. [31] proposed the use of big data to improve VTS benefit assessment within maritime administration, but operational evaluation frameworks capable of implementing this idea remain limited. Against this backdrop, introducing full-sample trajectory logic into maritime evaluation is not simply a technical improvement in data processing. It also provides a comparative basis for examining how traditional sampling approaches may shape observed valuation outcomes. Building on this intersection, the present study adopts a parallel comparative design inspired by recent developments in transport economics to examine differences between traditional and full-sample frameworks for VTS evaluation.

3. Methodology

3.1. *Empirical Strategy and Parallel Design*

This study addresses a central question: to what extent do different valuation frameworks shape the identification and representation of VTS economic value? To minimize interference from infrastructure changes and external operational shocks, a parallel comparative design is adopted in which a traditional sampling-based evaluation framework and a full-sample evaluation framework are implemented using the same vessel traffic dataset. By holding traffic conditions and data sources constant, the study compares how alternative evaluation settings influence valuation outcomes under an identical operational environment.

The empirical case focuses on Tianjin Port, one of the major hub ports in northern China. The port is characterized by high traffic density, heterogeneous vessel composition,

and substantial channel coordination demand, making it suitable for examining VTS-supported traffic organization under complex operating conditions.

An additional advantage of Tianjin Port lies in the relative stability of its operational environment during the study period. The main navigation channel was expanded in 2013, while the VTS system underwent hardware and algorithm upgrades in 2016 and 2018. By 2018, channel conditions, monitoring facilities, and traffic organization practices had largely stabilized. Accordingly, 2018 is selected as the primary observation window, reducing the possibility that valuation differences merely reflect infrastructure transitions or system adjustment processes. To examine whether the findings remain stable over time, the analysis is further extended to equivalent datasets from 2019 and 2020 for cross-year comparison.

Under the same traffic environment and shared data foundation, two valuation frameworks are implemented in parallel.

The first is a Legacy Framework, which reconstructs a conventional sampling-based maritime CBA logic developed under historical data constraints. This framework extrapolates annual benefits from representative monthly samples, estimates time savings using historical differences in average transit times before and after channel expansion (2012–2013 versus 2014–2015), and applies vessel-type average operating costs for valuation [10].

The second is a Full-Sample Framework, which uses complete vessel trajectory records to evaluate vessel movements at the individual level. This framework adopts the System Default Sequence (SDS) as an operational counterfactual benchmark and estimates time savings across different coordination scenarios using vessel-specific operating costs that account for heterogeneity among vessel types.

The full-sample framework is not treated as a measure of a single “true” value. Because traffic organization in the absence of coordination cannot be directly observed, all valuation approaches necessarily rely on some degree of rule-based assumptions and parameter settings. The purpose of this study is therefore not to determine which framework is absolutely correct, but to examine how differences in temporal benchmarks, sample coverage, and cost assignment are associated with changes in the estimated scale and composition of VTS economic value.

Under identical traffic conditions and a shared operational environment, differences between the two frameworks can thus be interpreted as reflecting how alternative evaluation settings shape observed valuation outcomes.

3.2. Data Integration and Heterogeneous Cost Mapping

3.2.1. Data Integration and Sample Construction

The empirical analysis draws on an integrated vessel traffic database maintained by maritime authorities. The database combines multiple operational data sources, including VTS system records, AIS trajectory data, radar observations, hydrological and meteorological monitoring data, as well as external operational information related to port dispatching, pilotage, and tug assistance. Details of the data sources are summarized in Table 1. Cross-system integration is achieved through vessel identifiers, primarily Maritime Mobile Service Identity (MMSI) numbers and call signs, allowing dynamic operational records to be linked with vessel-level static characteristics.

The study covers vessel movement records from 2018 to 2020. A total of 60,043 valid vessel movement records were identified for 2018, compared with 64,307 in 2019 and 59,549 in 2020. Given the relative operational stability following channel expansion and VTS system upgrades, 2018 is selected as the primary observation window, while data from 2019–2020 are used mainly to examine the temporal stability of the findings through cross-year comparison.

Table 1. Sources of VTS Data.

Data Sources	Data Content	Data Type	Acquisition Method	Update Frequency
VTS System	Real-time monitoring, Information services, Decision-making assistance, System management, Emergency information, etc.	Numeric, Text, image, AIS, GIS	Business generation, Website queries, Shared interfaces, Analysis and statistics	Real-time
Internet of Things (IoT)	Radar, VHF, CCTV, Hydrology, AIS, GPS, Meteorology	Numeric, Image, Text, Video, GIS, GPS	Sensing equipment, Testing equipment	Real-time /Periodic
External Business Information	Harbour dynamics, Pilotage tug dynamics, Agency terminal dynamics, etc.	Numeric, Text, Image	Proactive declaration, Website search, Shared interface, Targeted publication	Real-time /Periodic
Third Party Sharing	Customs, Maritime police, Cooperation agencies	Numeric, Text, Image	Directed Releases	Unscheduled

All coordination scenarios are identified directly from full operational records without additional sampling or statistical extrapolation. Data preprocessing focuses primarily on observations with missing time fields, duplicate records, or incomplete vessel characteristics. Only records sufficient to support trajectory matching and coordination-scenario identification are retained for analysis. After cleaning, vessel trajectories are integrated with operational context and cost information to support scenario-based valuation at the individual vessel level.

3.2.2. Vessel Classification and Traffic Composition

Tianjin Port operates under a dual-channel navigation system in which vessels of different sizes are subject to different routing permissions and traffic organization rules. Smaller vessels, generally below 146 m in length, typically use the shallow outer channel closer to the coast, whereas larger vessels mainly navigate through the deep-water main channel. To reflect actual operational practices, vessels are classified into four groups according to length: small vessels (≤ 146 m), medium vessels (146–200 m), large vessels (200–300 m), and ultra-large vessels (>300 m). This classification reflects channel organization practices while also allowing differences in coordination patterns across vessel categories to be examined. The vessel traffic composition for 2018 is presented in Figure 1.

3.2.3. Heterogeneous Operating Cost Mapping

To estimate the economic value associated with vessel time savings, this study draws on the *Drewry Annual Review and Forecast of Ship Operating Costs 2018/19* to construct a vessel operating cost parameter database. The dataset covers major vessel categories, age classes, and tonnage ranges, providing a basis for approximating the opportunity costs associated with vessel operations.

The selection of Drewry cost parameters is motivated by their broad use in maritime industry analysis and their coverage of vessel operating expenses across different ship categories and market segments. Although these industry-level estimates do not represent the exact realized cost of individual vessels, they provide a consistent reference for approximating the opportunity cost of vessel time. Given that the objective of this study is to

compare valuation outcomes under different evaluation frameworks rather than to estimate the absolute commercial profitability of each vessel, Drewry-based cost parameters offer a practical and comparable basis for heterogeneous cost assignment.

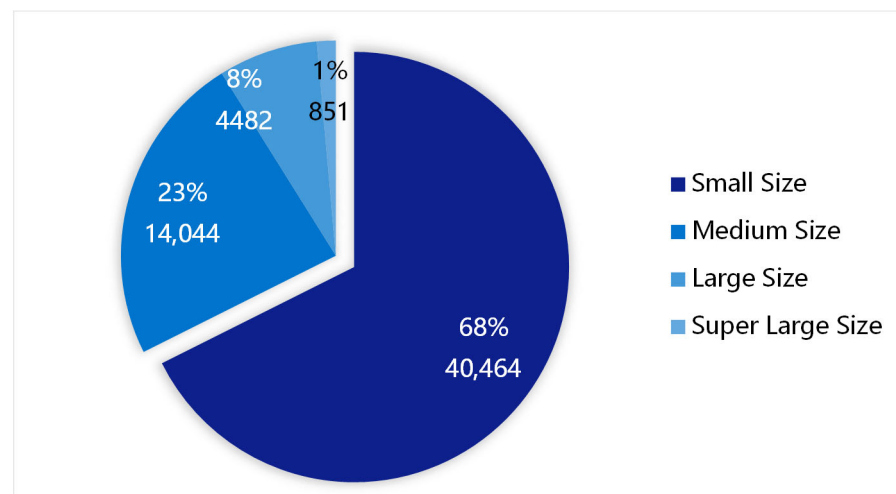


Figure 1. Traffic Composition by Vessel Length Cohort (Tianjin Port, 2018).

Using information recorded in AIS data, including vessel type, tonnage, and age, individual vessel trajectories are matched to corresponding operating cost parameters through a rule-based mapping procedure. For a small number of special-purpose vessels that cannot be precisely matched (e.g., engineering or public-service vessels), cost parameters are assigned based on tonnage and the closest comparable operational category. The resulting cost parameters are intended to provide a consistent approximation of market-based operating opportunity costs rather than a precise measure of realized commercial returns, thereby supporting comparable valuation across heterogeneous vessel types.

3.3. Algorithmic Pipeline and Parallel Evaluation Implementation

3.3.1. System Default Sequence (SDS)

In the absence of a directly observable “no-coordination” condition, evaluating the economic benefits of VTS requires an operational benchmark against which alternative traffic arrangements can be compared. To address this issue, the study constructs a System Default Sequence (SDS) based on the sequencing logic embedded in the Tianjin Port VTS system. Within the full-sample framework, the SDS serves as a rule-based reference sequence for estimating time differences associated with traffic coordination.

In practice, vessel traffic organization is jointly shaped by international navigational rules, port operational requirements, and local navigational practices. Vessel movements in VTS-controlled areas are generally organized according to operational rules, vessel characteristics, traffic conditions, and safety-related interaction constraints [32,33]. Accordingly, sequencing decisions are not arbitrary but reflect practical requirements for maintaining navigational order and managing vessel encounters. Under routine operating conditions, the baseline sequencing logic in Tianjin Port can be approximated through a simplified ordering template that assigns relatively shorter intervals to same-direction traffic and longer intervals to opposing-direction movements, reflecting differences in coordination constraints. The 30 min and 60 min intervals adopted in this study are not interpreted as universal separation standards. Instead, they represent simplified operational approximations of routine sequencing practices, where same-direction movements generally involve lower interaction constraints while opposite-direction encounters require longer coordination intervals. These parameters provide a consistent and reproducible benchmark for

counterfactual construction. In the baseline SDS specification, these operational spacing assumptions are represented by 30 min and 60 min intervals, respectively, providing a consistent and reproducible benchmark for comparison.

The SDS should not be interpreted as a complete absence of VTS management or a directly observable counterfactual state. Instead, it serves as a rule-based operational benchmark approximating the sequencing order that may emerge without further dynamic optimization. Time differences in the full-sample framework are defined as the difference between actual vessel transit timing and the timing implied by the SDS reference sequence. Accordingly, the estimated benefits reflect the time effects associated with dynamic coordination relative to a standardized operational baseline, rather than the total value generated by the VTS system itself.

3.3.2. Coordination Scenario Identification

To improve comparability across operational contexts, observable VTS coordination activities are grouped into three broad coordination mechanisms: weather-related coordination, channel-constrained coordination, and routine coordination. Although the underlying calculations rely on multiple operational modules, all valuation outcomes are aggregated according to these coordination mechanisms to facilitate comparison across scenarios.

1. **Weather-Related Coordination.** This category captures traffic organization under adverse meteorological conditions, particularly reduced visibility and strong winds. Coordination events are identified using VTS operational logs and meteorological records. Temporary restrictions, sequencing adjustments, and holding arrangements are incorporated by comparing actual vessel movements with the SDS reference sequence.
2. **Channel-Constrained Coordination.** This category refers to traffic organization associated with physical channel constraints or vessel maneuvering requirements, including width restrictions, temporary one-way navigation, and turning operations involving large vessels. Relevant events are identified based on vessel characteristics, navigational rules, and operational windows, after which timing differences between the SDS benchmark and observed scheduling are estimated.
3. **Routine Coordination.** This category includes regular traffic organization activities outside special operational constraints. Under Tianjin Port's dual-channel system, VTS may improve traffic efficiency through dynamic sequencing and mixed-navigation arrangements among vessels of different sizes. Estimated effects are derived from differences between SDS-implied ordering and observed vessel scheduling.

To avoid double counting, an exclusive hierarchical attribution rule is applied. Vessel movements are first screened for weather-related and channel-constrained conditions; once classified into a special coordination scenario, they are excluded from routine coordination calculations. This procedure ensures that estimated benefits remain mutually exclusive across coordination mechanisms.

The aggregate economic value of VTS coordination is calculated as follows:

$$B = \sum_{s \in S} \sum_{k \in K} N_{sk} \times \Delta t_{sk} \times C_k$$

where B denotes the total economic value, S represents the set of coordination scenarios, and K denotes vessel categories. N_{sk} indicates the number of vessels of category k under scenario s , Δt_{sk} represents the corresponding time difference, and C_k refers to the operating opportunity cost parameter derived from the Drewry cost database.

The estimated time difference primarily reflects changes associated with VTS coordination arrangements. At the same time, actual vessel movements may also be influenced by factors such as captain speed adjustments or other operational decisions. The resulting

estimates should therefore be interpreted as a reasonable approximation of coordination effects rather than a fully isolated measure of VTS intervention alone.

The main methodological challenges encountered during data integration and valuation are summarized in Table 2.

Table 2. Methodological Challenges and Solutions.

Methodological Challenge	Description	Analytical Solution
Multi-source data integration	Vessel movement information was distributed across heterogeneous systems, including VTS logs, AIS trajectories, meteorological monitoring, and port operational records.	Vessel MMSI and call sign were used to integrate dynamic vessel trajectories with static vessel attributes into a unified analytical dataset.
Coordination scenario identification	Raw operational records did not explicitly distinguish coordination scenarios such as weather restrictions, channel constraints, or routine scheduling activities.	A rule-based classification procedure was developed to identify vessel movements under predefined coordination mechanisms using VTS logs, operational regulations, and event windows.
Counterfactual benchmark construction	Vessel movements in the absence of dynamic coordination cannot be directly observed.	A rule-based SDS was established to approximate baseline sequencing under standard navigational rules.
Data incompleteness and inconsistency	Some vessel records contained missing timestamps, incomplete vessel parameters, or inconsistencies across systems.	A multi-step data cleaning process was implemented, including cross-system verification, missing value treatment, and outlier screening.
Heterogeneous cost assignment	Vessel operating costs vary substantially across vessel types, tonnage, and age profiles.	Vessel-specific operating cost parameters were assigned using Drewry cost matrices based on vessel type, deadweight tonnage, and vessel age.

3.3.3. Legacy Framework Reconstruction

To enable a systematic comparison, this study reconstructs a conventional sampling-based CBA framework as a benchmark for comparison. Consistent with long-standing VTS evaluation practices developed under data constraints, the framework reflects three common features frequently adopted in maritime CBA.

A key feature concerns the treatment of time savings. Rather than estimating coordination effects from real-time traffic organization, the framework applies historical differences in average vessel transit time before and after channel expansion (2012–2013 versus 2014–2015) as fixed parameters for subsequent valuation. Estimated time gains may therefore reflect both operational coordination and infrastructure improvements.

The framework further relies on representative monthly samples to estimate annual benefits, with results extrapolated to yearly totals. According to operational records, monthly observations typically cover approximately 8–15% of vessel movements, which may limit the visibility of frequent but small-scale coordination activities.

Economic valuation is also based on vessel-category average operating costs, without accounting for differences in vessel age, tonnage, or other operational characteristics, thereby smoothing heterogeneity in opportunity costs.

By contrast, the full-sample framework adopts the SDS operational benchmark, complete scenario identification, and vessel-specific cost mapping. Rather than treating either framework as a uniquely correct estimate, this study examines how differences in temporal

benchmarks, sample coverage, and cost assignment influence the estimated scale and composition of VTS economic value. The empirical implications are discussed in Section 4.

3.4. Robustness and Sensitivity Assessment

Because the empirical analysis is based on complete annual vessel movement records rather than sampled observations, conventional statistical inference designed for sampling uncertainty is of limited relevance to the present research design. Robustness is therefore assessed through cross-year validation and sensitivity analysis.

To examine temporal stability, the full-sample framework is extended from the benchmark year of 2018 to equivalent datasets from 2019 and 2020. These years differ in traffic composition, weather-related restrictions, and operating conditions, allowing the consistency of valuation outcomes across varying environments to be assessed.

In addition, sensitivity analysis is conducted to examine whether estimated benefits under the SDS benchmark are highly dependent on interval assumptions. Alternative separation intervals are introduced within a plausible operational range to assess whether the relative contribution patterns across coordination mechanisms remain substantively stable.

4. Results

4.1. Divergent Valuation Outcomes Under Different Evaluation Frameworks

To examine how alternative valuation frameworks shape the identification of VTS economic value, the analysis begins with the 2018 operational dataset under identical traffic conditions. To ensure comparability, only direct economic savings associated with vessel time reductions are included. Benefits that are difficult to directly observe, such as accident avoidance, broader social externalities, or input–output multiplier effects, are excluded so that all estimates remain traceable to observable trajectory and scheduling records.

The legacy framework estimates annual benefits using representative traffic samples and vessel-category average operating costs, whereas the full-sample framework evaluates complete vessel trajectories against the SDS operational benchmark and applies vessel-specific cost mapping. Because both approaches are implemented under the same traffic environment, differences in estimated outcomes primarily reflect alternative evaluation settings rather than operational variation. Table 3 reports the valuation results.

Table 3. Comparison of Valuation Outcomes Between Legacy and Full-Sample Frameworks (2018).

Coordination Mechanism	Legacy Framework	Full-Sample Framework	Relative Difference
Weather-related coordination (restricted visibility + strong winds)	324.99	215.41	−33.72%
Channel-constrained coordination (width restriction, encounter limitation, large-vessel turning)	3769.93	3659.07	−2.94%
Routine coordination	1329.49	6580.49	+394.96%
Total	5424.41	10,454.97	+92.74%

Note: Weather-related coordination includes traffic arrangements under restricted visibility and strong wind conditions. Channel-constrained coordination includes width restrictions, encounter limitations, and large-vessel turning operations. Routine coordination refers to regular traffic organization activities outside weather-related and channel-constrained scenarios. Unit: 10,000 CNY.

A more substantial divergence emerges in routine coordination. Under the full-sample framework, estimated economic benefits are nearly five times higher than those generated by the legacy framework. This finding suggests that frequent but small-scale coordination activities, although individually limited in impact, may be difficult to capture

through partial sampling. Because such activities are dispersed throughout continuous traffic operations, their cumulative contribution is more likely to be underestimated under sampling-based approaches and becomes more visible under trajectory-level full-sample evaluation [34].

Taken together, these findings suggest that differences between evaluation frameworks are not evenly distributed across coordination contexts. For highly structured operational scenarios, valuation outcomes tend to converge. By contrast, in routine traffic organization where benefits accumulate through repeated micro-coordination, observation granularity and sample coverage appear to play a more consequential role in shaping measured economic value.

4.2. Why Do Valuation Outcomes Differ Across Frameworks?

The comparison above suggests that differences between valuation frameworks are reflected not only in total estimated benefits, but also in the relative importance assigned to different coordination scenarios. In particular, the full-sample framework identifies substantially larger gains from routine coordination, whereas the legacy framework places greater weight on weather-related and channel-constrained scenarios. These differences appear to be associated with several embedded evaluation settings.

One important difference concerns the treatment of temporal benchmarks. The legacy framework estimates benefits by comparing observed transit times with historical averages, thereby implicitly incorporating long-term improvements in infrastructure and navigational conditions. By contrast, the full-sample framework evaluates vessel movements against an SDS-based counterfactual constructed within the same operational environment. As a result, the two approaches may capture different forms of time savings, particularly in weather-related or channel-constrained situations where operational disruptions are more visible.

Differences also arise from sample coverage. Traditional evaluations typically rely on monthly sampling and annual extrapolation, which may be sufficient for capturing infrequent but highly visible events such as severe weather restrictions or major channel controls. Routine coordination, however, often consists of repeated micro-adjustments in vessel sequencing, localized waiting-time reductions, and mixed navigation among vessels of different sizes. Although each intervention may produce only modest gains, their cumulative effect can become substantial over time. By matching vessel trajectories across the full operational year, the full-sample framework appears better suited to identifying these high-frequency coordination activities.

Cost assignment provides another source of variation. Traditional approaches generally apply average operating costs by vessel category, whereas the full-sample framework incorporates vessel-level heterogeneity. Because the opportunity cost of time varies substantially across vessel classes, averaging procedures may reduce the relative contribution of some high-value coordination activities. This effect appears more visible in routine coordination, where a wider range of vessel types is involved. The key differences between the two evaluation frameworks and their potential implications are summarized in Table 4.

Taken together, the observed differences do not simply suggest that one framework systematically overestimates or underestimates VTS value. Instead, they indicate that estimated outcomes depend partly on how coordination activities are observed and valued. Under clearly bounded situations such as severe weather or channel restrictions, the two approaches tend to produce comparable estimates. Under routine operating conditions, however, differences in observation granularity and cost treatment appear more likely to influence measured economic value.

Table 4. Core Evaluation Settings and Potential Implications.

Evaluation Dimension	Legacy Framework	Full-Sample Framework	Potential Implication
Temporal benchmark	Historical transit-time differences	SDS-based counterfactual within the same operational period	Legacy may over-attribute benefits from infrastructure to VTS
Sample coverage	Monthly sampling and annual extrapolation	Vessel-level matching using full-sample trajectories	Legacy may miss high-frequency, low-impact coordination
Cost assignment	Average operating cost by vessel category	Vessel-specific heterogeneous cost mapping	Legacy may undervalue time savings of high-value vessels

4.3. Cross-Year and Parameter Robustness

4.3.1. Cross-Year Robustness and Changing Traffic Conditions

To examine whether the full-sample framework remains stable under changing operational conditions, the same computational procedure was extended to equivalent datasets from 2019 and 2020. Cross-year comparison provides an opportunity to assess whether valuation patterns persist under variation in traffic intensity, vessel composition, and operational disruptions. During the study period, Tianjin Port recorded 60,043, 64,307, and 59,549 vessel movements, respectively, indicating broadly comparable operating scales across years. Table 5 reports the valuation results for different coordination scenarios. To facilitate interpretation, key operational indicators across years are reported in Table 6.

Table 5. Cross-Year Comparison of Full-Sample Valuation Results, 2018–2020 (Unit: 10,000 CNY).

Coordination Scenario	2018	2019	2020
Weather-related coordination	215.41	351.55	647.02
Channel-constrained coordination	3659.07	4204.25	4839.03
Routine coordination	6580.49	5573.19	5362.06
Total	10,454.97	10,128.99	10,848.11

Table 6. Key Operational Conditions Across Years.

Indicator	2018	2019	2020
Vessel movement records	60,043	64,307	59,549
Weather restriction events	89	96	120
Share of ultra-large vessels (>300 m)	1.42%	2.03%	1.94%

Overall, the valuation structure remains broadly stable across years. Routine coordination consistently represents the largest source of estimated benefit, accounting for approximately 53–63% of total value, followed by channel-constrained and weather-related coordination. This ranking remains unchanged throughout the study period despite variation in traffic composition and operating conditions.

The main findings also remain directionally consistent with the baseline comparison in 2018. Total benefits estimated under the full-sample framework remain substantially higher than those obtained under the legacy sampling-based approach, while the estimated contribution of routine coordination continues to exceed that of the legacy framework by a considerable margin. These patterns suggest that the larger cumulative contribution of high-frequency coordination is not confined to a single observation year.

Changes across coordination scenarios also appear consistent with observable operating conditions. Weather-related benefits increase over time alongside a higher frequency of

weather control events, which rose from 89 in 2018 to 120 in 2020. Similarly, the contribution of channel-constrained coordination remains substantial as the proportion of ultra-large vessels increased from 1.42% to nearly 2%, implying greater demand for one-way passage, encounter restrictions, and turning operations.

At the same time, annual fluctuations in estimated value suggest that VTS benefits do not vary mechanically with traffic volume alone. Changes in vessel composition, weather disruptions, and traffic organization may jointly influence the scale and composition of coordination benefits. Even under these changing conditions, however, routine coordination remains the dominant source of estimated economic value.

Taken together, the cross-year results indicate that the full-sample framework maintains relatively stable valuation patterns under different operating conditions while remaining sensitive to structural changes in the traffic environment.

4.3.2. Alternative SDS Interval Settings

The SDS interval settings were varied within a limited range because vessel sequencing in VTS operations is generally governed by minimum safety separation requirements rather than arbitrary managerial preference. Although interval values differ across ports according to channel geometry, traffic density, and operational practice, the underlying logic of maintaining minimum navigational separation is common across VTS environments. The alternative settings therefore function as scenario-based robustness tests rather than precise behavioral assumptions.

Because the SDS counterfactual depends on sequencing intervals, additional tests were conducted to examine whether moderate adjustments would materially alter the main findings. In addition to the baseline specification (30 min separation for same-direction passage and 60 min for opposite-direction encounters), two alternative settings were examined.

As shown in Table 7, interval changes affect the absolute scale of estimated benefits, while the broader valuation pattern remains stable. Shorter intervals reduce estimated benefits by bringing the SDS benchmark closer to observed vessel sequencing, whereas longer intervals generate larger estimates by widening the gap between default sequencing and actual coordinated operations.

Table 7. Alternative SDS Interval Settings and Main Results (Unit: 10,000 CNY).

SDS Setting	Routine Coordination	Total Benefit	Coordination Ranking
20/40 min	3127.60	6482.08	Stable
30/60 min	6580.49	10,454.97	Stable
40/80 min	15,714.40	22,137.43	Stable

Although absolute estimates vary across specifications, the substantive findings remain consistent. Routine coordination continues to account for a substantial share of estimated benefits, and the full-sample framework consistently produces larger estimates than the legacy sampling-based approach.

5. Conclusions

5.1. Main Findings and Methodological Implications

This study examined a central question: to what extent do evaluation frameworks shape the economic value attributed to VTS? Drawing on full-sample vessel trajectories and dispatch records from a major Chinese hub port between 2018 and 2020, the study

compared a traditional sampling-based approach with a full-sample evaluation framework under identical traffic conditions.

The comparison shows that differences in evaluation frameworks are reflected not only in the overall magnitude of estimated benefits, but also in how the sources of those benefits are understood. The full-sample framework consistently produces higher estimates of economic value while revealing a different composition of benefits. Under the legacy framework, weather disruptions and channel restrictions appear more prominent because of their visibility and concentrated effects. By contrast, the full-sample framework suggests that a substantial share of VTS value is embedded in routine coordination, where repeated small adjustments in sequencing and traffic organization accumulate over time.

These findings suggest that the same traffic system may generate different patterns of economic value depending on how operational evidence is captured and evaluated.

Part of this divergence appears to be associated with differences in temporal benchmarks, sample coverage, and cost assignment strategies. The aim of this study, however, is not to identify a single “correct” valuation. Rather, the findings point to a broader methodological issue: evaluation frameworks influence which coordination activities become visible in economic analysis. In digital governance systems that depend on continuous adjustment and real-time coordination, measured value may depend not only on operational performance itself, but also on the assumptions embedded in evaluation procedures.

5.2. Practical Implications for Maritime Governance

The findings carry several implications for maritime governance practice. In many VTS evaluations, investment appraisal tends to focus on severe weather, temporary restrictions, or other exceptional situations because their effects are more visible and easier to quantify. The results of this study suggest that such an emphasis may overlook an important source of long-term operational value embedded in routine traffic coordination. As vessel traffic becomes more complex and digitally managed, greater attention may need to be paid to the cumulative contribution of everyday coordination when evaluating VTS performance and public investment outcomes. Maritime authorities could consider supplementing event-based evaluation reports with annual full-sample estimates of routine coordination benefits, using existing AIS and VTS log data.

The growing availability of AIS records, VTS logs, and trajectory data also creates new possibilities for performance assessment. Evaluation approaches developed under historical data constraints necessarily relied on limited samples and average assumptions. High-resolution operational data now make it possible to observe coordination activities with greater continuity and detail [35], supporting more evidence-based assessments of how different coordination mechanisms function under changing operating conditions [36].

More broadly, the study highlights the need to reconsider how digital public infrastructure is evaluated. For systems characterized by continuous coordination and algorithm-supported operations, governance value may not always be concentrated in major interventions or easily observable events [37]. Evaluation approaches capable of capturing dispersed operational effects may therefore become increasingly important for public decision-making.

Similar challenges have also been observed in the evaluation of other transportation infrastructure systems. Previous studies have emphasized that cost–benefit analysis outcomes are influenced by methodological choices, baseline definitions, benefit estimation procedures, and underlying assumptions rather than representing purely objective measurements of project value [38]. Infrastructure appraisal studies have further highlighted that simplified assumptions and incomplete representations of operational conditions may introduce systematic biases into estimated benefits [39]. These observations are consistent

with the findings of this study, suggesting that evaluation frameworks do not merely measure infrastructure value but also influence which operational effects become observable and quantifiable. In this sense, the methodological sensitivity identified in VTS evaluation reflects a broader challenge in the economic assessment of increasingly data-driven transportation systems.

From a management perspective, maritime authorities may consider establishing routine VTS performance monitoring systems based on trajectory-level indicators, such as accumulated vessel waiting-time reductions, frequency of coordination events, and benefits by vessel category. Such indicators could complement traditional evaluation reports that mainly emphasize major incidents or exceptional operating conditions. In addition, future VTS investment appraisals could incorporate full-sample operational evidence to periodically update benefit estimates rather than relying solely on historical assumptions.

5.3. Limitations and Future Research

The empirical analysis is based on a single large hub port, although the observation window extends across three years. Differences in channel configuration, traffic intensity, and vessel composition may influence how alternative evaluation frameworks perform in other operational settings. Therefore, the conclusions of this study should be interpreted primarily for large hub ports characterized by high traffic density, heterogeneous vessel composition, and continuous VTS-supported coordination. Whether similar valuation patterns exist in smaller ports or ports with different traffic structures requires further comparative investigation.

The counterfactual benchmark developed in this study relies on system rules and default sequencing logic to approximate vessel movements in the absence of coordination. Although alternative SDS interval settings produce structurally consistent results, the benchmark remains a rule-based approximation rather than a directly observable operational state. The study should therefore be understood primarily as a comparison of evaluation frameworks rather than an attempt to determine an absolute “true” value of VTS coordination.

The broader evaluation logic is not unique to Tianjin. The framework relies primarily on data types commonly available across modern VTS environments, including vessel trajectories, movement sequencing records, and coordination logs. Likewise, the SDS benchmark reflects a generalized operational principle of maintaining safety-based vessel separation, although interval thresholds may require local calibration according to navigational conditions and management practices. Future research could refine counterfactual construction through historical operational records, behavioral modeling, or adaptive machine-learning approaches.

Finally, the valuation model focuses primarily on direct economic benefits associated with vessel time savings and operating costs. Wider externalities—including environmental effects, supply-chain spillovers, and broader welfare impacts—remain beyond the scope of the present analysis. Extending the framework to incorporate these dimensions would help broaden understanding of the public value generated through digital maritime governance.

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